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A Greenhouse-Gas Information System - Monitoring and Validating Emissions Reporting and Mitigation - Chapter 2: Requirements Framework

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Disclaimer

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Chapter 2. Requirements Framework

Chapter Summary

The present study on a proposed greenhouse-gas information system (GHGIS) was undertaken without the benefit of requirements and specifications that will ultimately drive its choices and architecture. The discussion in this chapter attempts to develop a *requirements framework* that can be relied on to make choices between desired accuracy, precision, and confidence, vs. cost, schedule, and other elements.

The accuracy or precision of the GHGIS (top-down) components required to *validate* reporting and international commitments depends on factors determined by the nature of the commitments as well as the goals of the users. The present study focuses on the task of measuring GHG emissions and attributing anthropogenic surface fluxes. This chapter explores possible emissions pathways that depart from targets and makes a number of assumptions about the needs of users to detect and quantify such departures, regardless of whether they are the result of inadvertent or willful reporting errors. Such user needs would be used to set GHGIS requirements.

Findings

1. GHGIS requirements from which specifications on accuracy, precision, data and modeling uncertainty quantification (UQ) can be derived have not been set.
2. Based on assumptions documented below, if GHGIS is to validate total, country-level GHG emissions against annual targets, then *accuracies* will likely need to be in the range of ± 5-18%, depending on emissions pathways and the required levels of confidence. These estimates would be refined or adjusted, accordingly, in response to requirements.
3. If GHGIS must quantify *changes* in emissions relative to a baseline year and based on the same assumptions as in Item 2, above, then the required *precision* is ±5-18%.
4. High *precision* is easier to achieve than high *accurac*y and may require a GHGIS that is operational in the *baseline year.*
5. The need for high precision could be somewhat relaxed if top-down GHGIS components are used in combination with bottom-up inventories, however, at the cost of losing some benefits of (independent) validation.

Recommendations (Phase-1 Development)

1. GHGIS development should include the ability to establish reliable baseline estimates in regions of interest early on.
2. GHGIS should supplement the lower precision of results from its early development phase with capabilities to validate mitigation actions and support and incorporate all-source information.

Recommendations (Phase-2 Development)

3. As a guideline, GHGIS should adopt a methodology that will yield an overall precision of

anthropogenic emissions of ±10%, or better.

4. GHGIS should be capable of measuring multiple greenhouse gases, including CO_2, methane (CH_4), nitrous oxide (N_2O), as well as carbon monoxide (CO), and a number of fluorinated gases.
5. GHGIS should aim to also attribute emissions by economic sector.
6. GHGIS should be designed to provide periodic emissions estimates, such as quarterly and annually, covering specific countries, emitters, industries, or economic sectors in response to GHGIS-customer needs.

Recommendations Overview and Reasoning

GHGIS includes an important top-down component based on measurements, which aims to monitor country-level greenhouse-gas (GHG) emissions to provide independent *validation* of emissions declarations, mitigation measures, and as well as treaty commitments and compliance. Current state-of-the-art, bottom-up estimates are based on engineering calculations ("inventories"). The top-down GHGIS component does not rely on self-reported bottom-up data. These can be used either as independent input, or to augment top-down estimates to improve both. At present, inventories provide the only estimates. They are likely to remain better-suited for emissions estimates by sector than may be achievable by top-down measurements alone, at least in the near and intermediate term. The top-down and bottom-up components that GHGIS will integrate should be viewed as best used in conjunction.

The accuracy or precision required of GHGIS to monitor and validate international commitments depends on a number of factors, including:

1. The specificity of the commitment and whether it is conditioned on other estimated data that must be taken into account, such as emissions per unit GDP;
2. the magnitude of the departure from target emissions that must be detected and quantified;
3. how quickly the departure must be detected;
4. the probability of detection, if departures from emission agreements occur; and
5. the required confidence level before reporting that a departure has occurred.

Further, the commitment can take various forms. It may be on total GHG emissions or a subset of gases and sectors. It may be on absolute emission levels or on a compound metric like carbon intensity (i.e., emissions per dollar of Gross Domestic Product [GDP]), or national per capita emissions. Uncertainties in these denominators (GDP or population) would need to be taken into account. The commitment may also be the implementation and maintenance of specific mitigation actions, such as slowing or reversing deforestation, or even afforestation.[1] The present study focuses on the task of measuring GHG emissions and attributing anthropogenic surface fluxes that will be an essential component in almost any case.

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[1] *Reforestation* refers to restoring a forested area and forest growth, i.e., where a forest has previously existed. *Afforestation* refers to the establishment and maintenance of forests in areas not forested previously, or not forested in a given reference year.

In support of estimations with the required precision or accuracy of GHGIS reports, it is proposed that the system be capable of detecting departures with a greater than 50% probability, within four years of the start of the departure, and a 95% confidence level that the departure is occurring when reported. Four reasonable emission pathways were explored that depart from target emissions (see Fig. 2-1). If GHGIS is framed as a tool to validate total, country-level GHG emissions against annual targets, then the required accuracy is in the range of ±5-18%, depending on the emissions pathway (see Table 2-1). If GHGIS must establish *changes* in emissions relative to a baseline year, then the required *precision* is ±5-18%. This scenario requires a GHGIS that is operational in the baseline year, but has the advantage that a ±5% precision, for example, is easier to achieve than ±5% accuracy because certain systematic errors will not exert the same influence on the former.

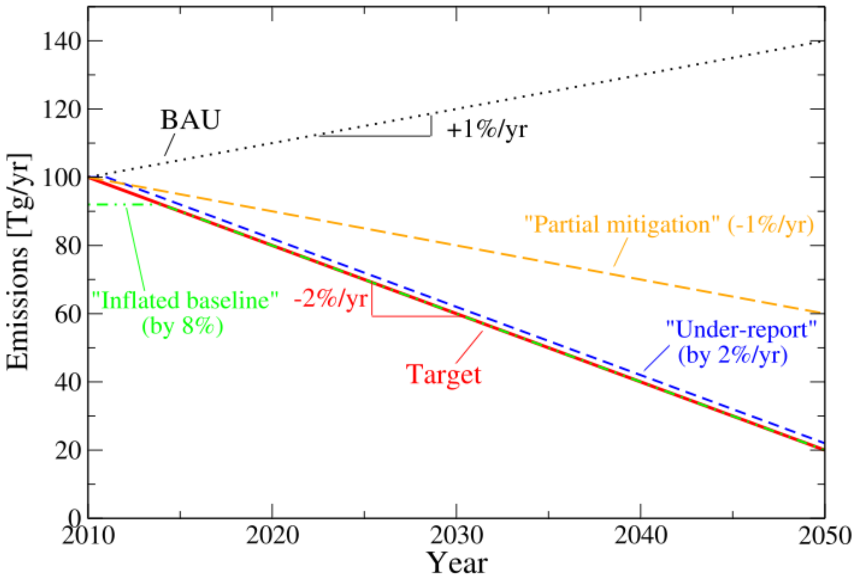

Figure 2-1. Potential emissions trajectories for the hypothetical country Midlandia. According to an emissions reduction agreement, "Target" emissions drop by 2% per year, relative to the baseline year 2010, achieving a 20% reduction by 2020 and an 80% reduction by 2050. If no mitigation actions are taken, Midlandia follows the BAU (Business as Usual) path, increasing emissions by 1% per year. Each scenario is described in detail in the text.

Table 2-1. Required measurement accuracy to achieve proposed detection criteria for the departure scenarios shown in Fig. 2-1: 50% probability of detection at 95% confidence within 4 years.

Scenario	Accuracy required
Under-report	+/-5%
Partial mitigation	+/-6%
Inflated baseline	+/-12%
BAU	+/-18%

The need for high precision could be relaxed if the top-down GHGIS components are used to provide a validation check on bottom-up inventories that, in turn, would be compared to target emissions. Inventory reporting provides multiple points of comparison for emissions, e.g., by gas and sector instead of a single, annual total. To exploit the full information, GHGIS must be capable of measuring multiple gases, attributing anthropogenic emissions by sector, and potentially attributing anthropogenic emissions by region and for relatively short time periods, while accounting for seasonal variations. This capability will enable integration of a variety of external and all-source information and improve reliability and flexibility in the detection process. The proposed GHGIS should have these capabilities with an overall precision for the quantification of anthropogenic emissions of ±10%.

To measure total emissions trends with this precision, several GHGs must be monitored and measured. In particular, the proposed GHGIS should include fossil-fuel carbon dioxide (CO_2), biogenic CO_2, methane (CH_4), nitrous oxide (N_2O), and a number of fluorinated gases.

On the question of which countries to cover, one may chose to cover 80% of global emissions. This can be adjusted in the future, as policy and other needs evolve along with GHGIS capabilities. The particular countries to include is a separate question, also a matter of policy, but will likely include at least eight emitters (with the European Union [EU] considered as a single emitter) and may reasonably include tens of countries, ranging widely in size and geography. The required spatial scale/resolution for GHGIS will then vary from country to country.

As an initial benchmark, a horizontal spatial resolution in the range of 10 to 50 km for reporting anthropogenic emission sources is proposed, with planning to refine this further as experience is gained and future GHGIS requirements dictate and evolve. This would allow sub-national emissions estimates in some larger countries, although, at this resolution, smaller countries may not be distinguishable from their neighbors. A higher (finer) horizontal spatial resolution for *measurements* and localized anthropogenic source retrievals is likely to be necessary to support the horizontal resolution in GHGIS reports, depending on emitter types and the geographical details and distribution of the anthropogenic emission sources (e.g., localized power plants vs. distributed transportation corridors).

The GHGIS envisaged provides anthropogenic emissions estimates quarterly and annually for comparison with inventory reports, and certain economic data to be released quarterly or monthly. However, both anthropogenic and natural GHG emissions vary substantially, both geographically and temporally, i.e., on seasonal, hebdomadal (weekly), and diurnal (daily) cycles, so GHGIS must internally aggregate emissions estimates on shorter time scales.

The discussion above summarizes the high-level requirements framework to help the GHGIS design if it is to be used as a tool to monitor and validate national and international emissions targets and treaty commitments. Since the nature and specifics of such future commitments are not known at this time, and perhaps not for some time to come, a general requirements framework was defined for the present study, although additional assumptions were necessary to arrive at some quantitative conclusions.

2.1 Introduction

Monitoring, reporting, and verification (MRV) is an essential component of international environmental treaties (Barret 1998). Recently, the Bali Action Plan called for “measurable, reportable, and verifiable” GHG mitigation actions and commitments (Ellis and Moarif 2009).

The Copenhagen Accord included a provision for transparency of GHG emissions and the effectiveness of mitigation actions for both developed and developing countries (Houser 2010). Effective MRV will allow countries to agree to and implement actions with confidence that they will know if other countries comply and abide by their agreements. It also allows both individual countries as well as the international community to track the effectiveness of mitigation measures and forecast whether implemented measures will suffice to meet policy goals.[2]

GHGIS is envisaged as having the capability to provide monitoring of country-level and sub-national level GHG emissions, and the independent validation of emissions declarations, mitigation measures, and treaty commitments. Specific design and significant resources are required to develop a GHGIS that can perform these tasks. The desired monitoring precision and the nature of the commitments to be validated will dictate the ultimate form and cost of GHGIS.

2.1.1 Bottom-Up GHG Inventories

Bottom-up estimates based on reporting and engineering calculations (“inventories,” or “emissions inventories”) provide the current methodology for GHG estimation (International Energy Agency [IEA]/Organization for Economic Cooperation and Development [OECD] 2010). Under the United Nations Framework Convention on Climate Change (UNFCCC), Annex-1 parties (developed countries) must submit annual inventories of GHG emissions to the UNFCCC Secretariat. Procedures and guidelines on how to prepare inventories are provided by the UNFCCC and the submissions are subject to review by independent experts to assess their correctness and compliance. However, no policies or procedures exist at this writing to enforce compliance, or address non-compliance, other than the exchange of information and attempts at reconciliation.

Estimates of national GHG emissions are calculated by summing up emissions from dozens of individual “source categories.” Each source category, for example, “steel mills” or “wastewater treatment,” has a defined procedure for calculating emissions. In general, the calculation starts with “activity data,” which typically derive from economic reports or business surveys, and include such figures as the number of gallons of gasoline sold and the number of tons of cement produced. Activity data are then multiplied by “emissions factors,” such as the average number of tons of CO_2 released per ton of cement produced and the average mass of carbon emitted per gallon of gasoline burned. Emissions factors are derived from engineering models of various processes (such as cement manufacture), chemical analysis of fuels, and emissions measurements at particular representative sources, such as vehicle tailpipes and boiler smoke stacks (EPA 2010).

Uncertainties in national GHG emissions estimates are introduced by uncertainties in activity data, emissions factors, and by the definitions of source categories that may either overlap (double-count) or omit certain sources. In some cases, source categories are intentionally omitted because procedures or data with which to estimate associated emissions are not agreed upon, or are incomplete. At present, the US GHG Inventory reports a 95% confidence level in the uncertainty of net GHG emissions of -2 to +7%. The uncertainty range for CO_2 emissions from

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[2] By way of example, if a particular set of mitigation actions is undertaken to decrease emissions by a certain percentage, an MRV system would reveal if the mitigation actions have achieved the intended target(s).

fossil fuel alone is -2 to +5% (EPA 2010). However, these uncertainty ranges should be viewed as *consistency* estimates of reported inventories. The ranges do not account for omitted source categories and are not *validated*, i.e., they are not confirmed by independent means at this time.

Bottom-up inventories with a precision similar to that reported by and for the United States require significant infrastructure and expertise. Non-Annex-1 parties to UNFCCC (developing countries) currently provide GHG emissions estimates of varying frequency and quality, with associated uncertainties that are accepted as being much larger (NRC 2010a).

In this chapter, *accuracy* refers to the uncertainty of absolute emissions measured by GHGIS, e.g., for a given country in a given year. The term *precision* refers to the uncertainty range in *differences* in emissions and, in particular, differences relative to a baseline year. Unless otherwise noted, all uncertainty ranges (such as ±10%) correspond to a 95% confidence interval. When a bottom-up inventory report is provided in the context of a treaty, or some other commitment where it serves as an official statement of country-level emissions, it will be referred to as a *declaration*, or *declared emissions*. The terms *verification* and *validation* are used as defined in the Introduction (Chapter 1) and amplified in Appendix C.

2.1.2 The Value of Independent Methods

Bottom-up inventories hold the promise of high precision and can provide substantial detail about GHG emissions sources. However, emissions inventories are the product of self-reporting. Errors and ambiguities may arise that are either inadvertent (i.e., the result of human error, or an inability to compile and report accurate data that represent a complex undertaking), result from the omission of certain sources, or even willful misreporting. Some checks may be made for internal consistency and against other data sources, but inventory reports that have not been independently verified and validated may not be and need not be accurate, or accepted as such.

If and when consequences are attached to the emission of GHGs, either in the form of charges for over-target emissions, or in the form of incentives to reduce emissions, emitters and those who aggregate and report inventories may have incentives to slant what they are prepared to report. Thus accurate inventories depend on both the *ability* to collect accurate data and analyze it correctly and the *willingness* to issue accurate reports. This is not to say that inventories are not without value, but rather that they need to be seen as one part of a system, which in its entirety allows for verification and validation.

Because GHGIS will depend on measurements and data that are independent from inventories, e.g., atmospheric measurements, it can provide a means of validation of emissions estimates not available through current methods or other means. Additionally, because atmospheric measurements can be made in and by countries or organizations not controlled by the country being monitored, GHGIS can provide independence in a way not available through self-reporting. It is this feature – the potential to provide independent validation – that makes GHGIS particularly valuable in supporting the assessment of mitigation actions and compliance of international commitments, in addition to its many science and other uses.

2.1.3 Use of GHGIS Products

GHG emissions estimates and other GHGIS products can serve many useful purposes, including substantial contributions to Earth science and climate science, monitoring of economic and other activities that depend on fossil-fueled energy production, and for other purposes, as discussed in the Introduction (Chapter 1) and throughout this report. However, the primary purpose of GHGIS is in the context of MRV, or MRV&V, and the facilitation and monitoring of climate-change and emissions-mitigation actions. The goal is to hold countries to their commitments and allow countries to make stronger commitments with confidence that others' commitments are also monitored and honored. Accordingly, the primary benefit of GHGIS is not achieved by accurate outputs alone, but from the expectation that GHGIS outputs will be accurate and definitive and, in turn, induce behavioral change by governments or international actors.

This chapter primarily focuses on the required accuracy and scope of GHGIS estimates. However, estimates derived from GHGIS products must also be convincing to outside parties. This may be achieved through features such as transparency, traceability, and independent review, with the inclusion of relevant stakeholders in those aspects of GHGIS design and operation that are best shared. Existing multilateral regimes generally rely on expert and peer review as part of the MRV, or MRV&V, process, and the automatic public release of inputs and outputs of review (e.g., Pew Center 2010). Of course, the particular approach to transparency and assurance is a matter of policy and cannot be addressed here in broad terms. Later chapters will discuss specific issues in assuring quality and credibility of GHGIS inputs and outputs.

2.1.4 Goal of this Chapter

The goal of this chapter is to lay out the requirements framework for a GHGIS that is useful for monitoring of country-level GHG emissions and the independent validation of mitigation commitments. Currently, there is no authoritative source dictating requirements for a top-down GHG monitoring system. This chapter attempts to define a starting place that bridges a reasonable expectation of what will be required to achieve policy goals, on the one hand, and projected technical capabilities of such a system, on the other.

The proposed requirements framework does not address sovereignty issues and the political ownership of GHGIS. Ground-level and airborne measurement in the country of interest are assumed to be available, i.e., we assume local access. Further, remote-sensing measurements from space are not subject to denied-territory limitations. This issue is discussed further in subsequent chapters. Neither is the legal status of GHGIS addressed, e.g., whether it exists within a treaty framework or whether its findings may initiate sanctions or proceedings, or whether it is intended to serve the purposes of US policy-makers alone.

The type of commitments made and the type of validation desired has a substantial impact on the specific GHGIS requirements. The next section discusses a number of possible framings of GHGIS and its role in validation. The section concludes with a set of working assumptions about how GHGIS could be used. The following sections address six high-level design criteria: country coverage, coverage by greenhouse gas, spatial resolution, temporal resolution, accuracy, and sectoral attribution. The chapter concludes with a summary of findings.

2.2 Potential Framings of GHGIS and Validation

GHGIS requirements depend on how validation and top-down emissions measurements are framed in the context of global climate-change and emissions mitigation. Traditionally, commitments are thought of in terms of cuts to total, country-level GHG emissions over time. The Kyoto Protocol provides the prime example. However, other types of commitments may take hold, such as "GHG Intensity," i.e., GHG emissions per unit of GDP. Intensity targets were set voluntarily by the United States during the Bush administration (Pizer 2005) and recently by China, in advance of the Copenhagen conference (Worthington 2009). GHG emissions per capita have also been frequently proposed (Baumert et al. 2005). To verify either type of commitment, one would need to verify both GHG emissions and either GDP or population, as appropriate, each with associated uncertainties and, possibly, manipulation. The focus of this report is the measurement of the anthropogenic GHG emissions component, the need for which is not diminished by composite metrics, such as GHG intensity. However, the need for complementary efforts to monitor and verify other components is also acknowledged. It is assumed that these components will be provided, or be integral, to GHGIS, which will integrate them into an overall top-down and bottom-up reconciliation and reporting to meet specific requirements.

Even focusing on GHG emissions, commitments may take a variety of forms that dictate expected roles of GHGIS. Such alternative "framings" are discussed below. Each has implications for the accuracy, precision, and scope required of GHGIS. It is also possible that countries may commit to particular mitigation activities, without reference to emissions metrics *per se*. Verification of activities is discussed as one of the framings below and, more generally, in the Introduction (Chapter 1) and in Appendix C. We conclude this section with a summary of our working assumptions and conclusions regarding some useful GHGIS framings.

2.2.1 Top-Down and Bottom-Up Measurement Components

Framing the bottom-up and top-down measurements as methods of contributing to the same goal – monitoring (a country's) GHG emissions – then GHGIS must accept as an uncertainty quantification (UQ) requirement an integration of top-down measurements that meet precision and accuracy uncertainties that are comparable to, and ideally better than, those of bottom-up inventories. Otherwise,

1. one might elect to choose inventories, if only one system could be chosen, or
2. GHGIS may offer little additional information when the products of the two systems are combined.

If one wished to validate one system against the other, GHGIS would need accuracy comparable to that of inventories, otherwise inconsistencies may be difficult to distinguish from known errors (this problem is statistically analogous to detecting departures for validation purposes, discussed in the next section). In short, *information from bottom-up and top-down reconciliation flows from variances between the two that exceed their combined uncertainties*.[3]

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[3] Top-down (GHGIS) uncertainties could be larger than those of inventories and still useful. By way of example, if the (claimed) inventory uncertainty was 5% and the assessed top-down uncertainty was 10%, valuable information would derive from a variance between the two of 20%.

Framing bottom-up and top-down measurements as components of equal significance would be appropriate if the goal is to validate the two types of measurements against each other, whether both are made in good faith or not. For example, if the United States develops a GHGIS for domestic monitoring to detect systematic errors for its own purposes, this framing would apply. However, in terms of international commitments, there is a qualitative difference between the measurement systems. The feature of independence, either from control of the country being measured or simply from bottom-up inventory methods, is important.

On a related note, objections to strong MRV requirements at the recent Copenhagen conference cited "intrusiveness" (Eilperin 2009). Thorough review of an inventory requires a volume of reliable economic data that may be considered intrusive to a country, such as fuel sales and detailed records of the development and operation of industrial facilities. Depending on the GHGIS structure, it may be considered intrusive in terms of measuring emissions within a country, but this exposes information of a different sort. In US law, emissions to the environment are considered public information and not subject to privacy restriction or trade-secrets protections. On the other hand, some inputs to bottom-up accounting methods, such as the types of equipment used within industrial facilities, are considered confidential business information and shielded from public view (e.g., EPA 2009). If international law follows this precedent, GHGIS may achieve a more palatable scrutiny than alternative methods of verification and validation using inventories alone.

For these two reasons, i.e., independence and less economic intrusiveness, GHGIS can provide a qualitatively different function than that provided by bottom-up inventory reporting systems.

2.2.2 GHGIS to Detect Departures from Absolute Emissions Targets

The most direct use of GHGIS for monitoring or treaty verification (validation of emissions and mitigation actions) would be to measure total, country-level GHG emissions and compare them with applicable emissions targets on an absolute scale. GHGIS would detect departures from targets or from declared emissions, regardless of whether departures are unintentional (mistakes), intentional (cheating), or within the uncertainty bounds of the reported values; *the lower the GHGIS uncertainties, the smaller are the departures that could be detected*. In this framing, GHGIS alone could trigger procedures for corrective action when departures are detected, or it could supplement and trigger other means of validation.

Figure 2-1 shows a simplified set of GHG emissions trajectories for a hypothetical industrialized country, Midlandia, with emissions in 2010 of 100 $\mathrm{MtCO_2e}$ (million tons carbon dioxide equivalent; cf. Chapter 1). The trajectories represent a range of potential scenarios. Target emissions are based on an assumed 20% emissions reduction by 2020 and an 80% reduction by 2050, i.e., a reduction of 2% each year relative to the baseline year 2010. The Business as Usual (BAU) trajectory increases by 1% each year relative to the baseline, which is roughly the emissions growth of the United States in the period 1990–2008. Other scenarios are also shown for which emissions depart from targets. None of the scenarios are meant to represent accurate predictions of a particular country's emissions pathway, but rather are meant to illustrate the scale of departures that GHGIS could be called upon to detect.

Emissions pathways for a developing country could show much higher growth rates. For example, China's emissions grew at an average rate of 5.4%/yr over the period 1979−2006 (Zheng et al. 2008). In contrast, *relative* reduction targets for developing countries may be modest. For example, one estimate finds that China's commitment before the Copenhagen conference to a 40-45% reduction in GHG intensity by 2020 amounts to only a 12% emissions reduction by that year from BAU (Worthington 2009). Thus relative changes in emissions that must be detected are not necessarily larger than for developed-country scenarios.

Assume that Midlandia commits by treaty to the target emissions trajectory shown in Fig. 2-1, but actually follows the BAU trajectory. This may be the easier detection problem for GHGIS. In the first year covered by the treaty, there is a 3% discrepancy between target and actual emissions. Figure 2-2 illustrates this at the end of the first year. The curves in this figure assume that GHGIS measurement uncertainties are ±5% (as defined by a 95%, or 2σ confidence interval), which is a rather ambitious assumption.

Figure 2-2 shows that the probability distribution of measurements one would expect to make if Midlandia's emissions are on target (the "noise" distribution) overlaps substantially with the distribution of measurements one would expect to make if Midlandia is instead following BAU (the "signal" distribution).

As with most signal-detection systems, a "decision threshold" is required, above which action is triggered if GHGIS reports emissions above this threshold. The action could range from initiating further investigations, to starting discussions with Midlandia to better understand the "discrepancy," to imposing sanctions on Midlandia for violating the treaty. Wherever the threshold is set, there is a chance that one would detect Midlandia as above target, when it is not, i.e., a "false positive," or that Midlandia would depart from targets undetected, i.e., a "false negative."

The choice of a decision threshold depends on the seriousness of the action that will be taken – imposing sanctions would likely require a very high threshold, for example, while a secondary investigation triggered by a less-strict threshold might be routine. A *priori* beliefs about the likelihood of emissions departures could be taken into account as well.

Formal treatment is not possible here, so it is assumed for illustrative purposes that a 95% confidence level that Midlandia is off target is required before taking any action. Equivalently, one could say that there should only be a 5% chance of accusing Midlandia of a departure when they are actually on target, i.e., a "false-positive rate" of 5%. The 95% confidence decision threshold is also shown in Fig. 2-2. The red-hatched area to the right of it demarks the 5% false-positive rate. The larger, blue-hatched area to the right of the decision threshold indicates the probability of detecting a departure if it occurs, i.e., the "true-positive rate." In this case, the detection probability is 32%. That is, if Midlandia is above target, the probability that GHGIS will return a measurement that allows us to say so with 95% confidence is 32%.

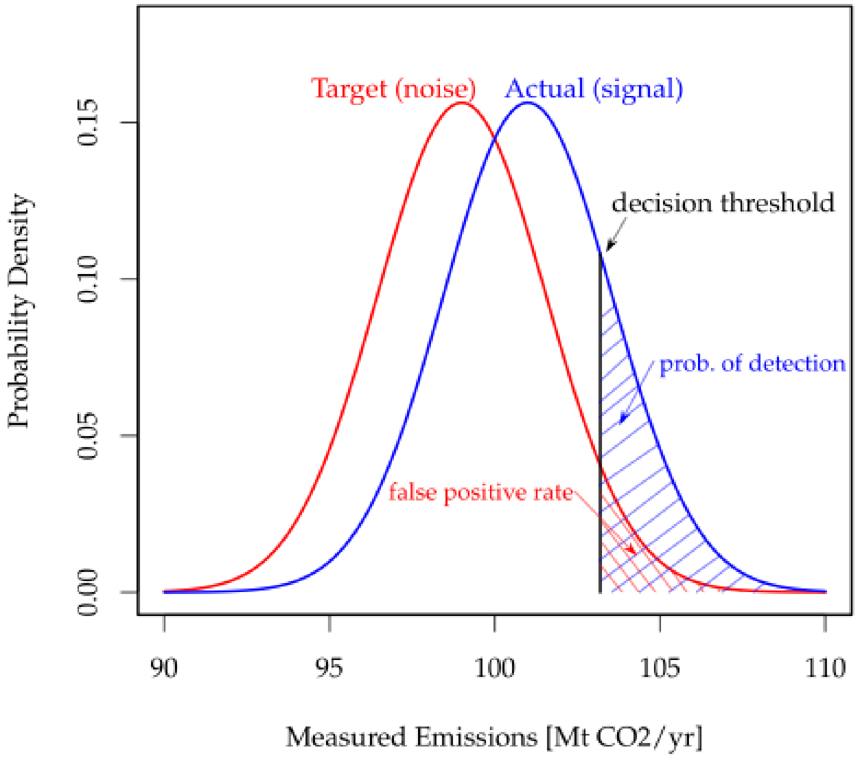

Figure 2-2. Distribution of measured values given compliance (at emissions = 98, the "target") and noncompliance (at emissions = 101, "actual") with a measurement uncertainty of ±5% and a decision threshold of 95% confidence (5% false-positive rate).

Whether a 32% probability of detection is sufficient is a question whose answer is a matter of policy. If one is concerned with intentional departures from targets (cheating), a reasonable goal may be to create a "culture of compliance" where cheating would generally be rare. This has been the case with most past environmental treaties (Barret 1998). A reasonable means of supporting a culture of compliance is if detecting cheating becomes more likely than not (probability of detection > 50%). By this criterion, the hypothetical detection problem depicted in Fig. 2-2 is not tenable. However, considering the time scales involved, it may not be necessary to detect departures the first year they occur. Measurements and integrated assessments can be performed over several years to build confidence by statistical accumulation, or other information, to discriminate between one trend versus another. In the BAU example, as time progresses, one gains both through repeated measurements and an ever-widening gap (strengthening signal) between actual and target emissions. Figure 2-3 shows the cumulative probability over 10 years of detecting a departure for several different GHGIS uncertainty levels. In this figure, GHGIS can be seen to meet the proposed requirements in the second year, with a ±5% uncertainty, in the third year with a ±10% uncertainty, and in the fifth year with a ±20% uncertainty.

An alternative approach to presenting the detection problem depicted in Fig. 2-3 (and Figures 2-4 through 2-6, discussed below) is in terms of ROC (Receiver-Operator Characteristic) curves. The ROC curve plots the probability of detection versus the false positive rate. The area under the ROC curve (AROC) is technically a better characterization of a detection system than the probability of detection because it does not require an *a priori* establishment of a decision threshold. However, AROC is more difficult to relate to policy goals. For interested readers, several ROC curves analogous to Figs. 2-3 through 2-6 are presented and discussed further in Appendix D.

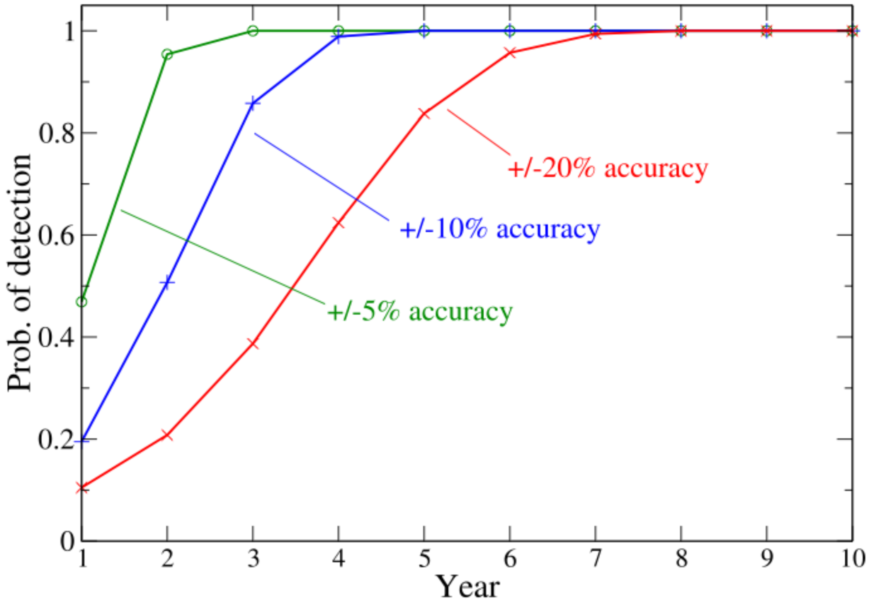

Figure 2-3. Cumulative probability of detecting a departure from target emissions, if actual emissions follow the BAU scenario (Fig. 2-1). The decision threshold is set at 95% confidence (5% false-positive rate, as in Figure 2-2). Each curve is labeled by the GHGIS measurement uncertainty (accuracy), represented by the relative 95% confidence interval. Each year, the probability of detection increases because of repeated measurements and the increasing discrepancy between target and actual emissions.

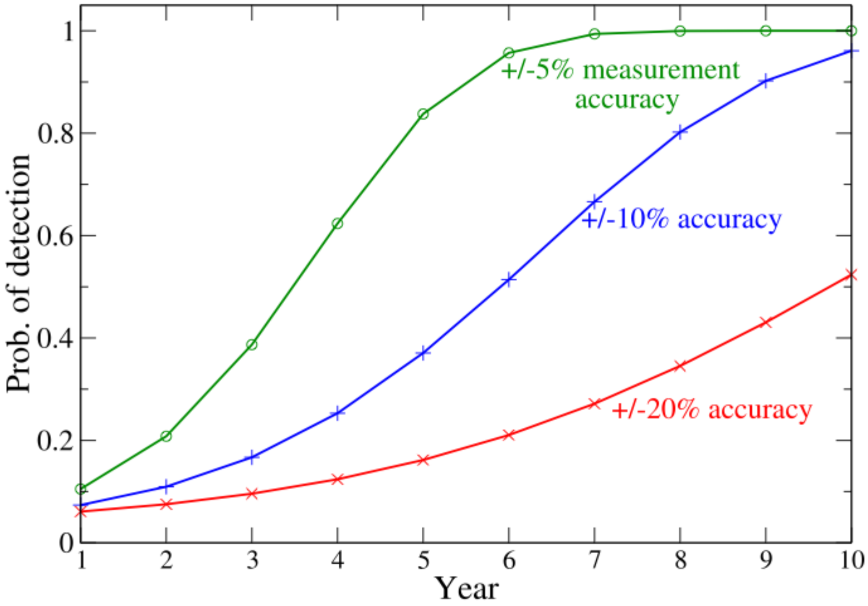

Figure 2-4. Cumulative detection probability for the "partial mitigation" scenario shown in Figure 2-1.

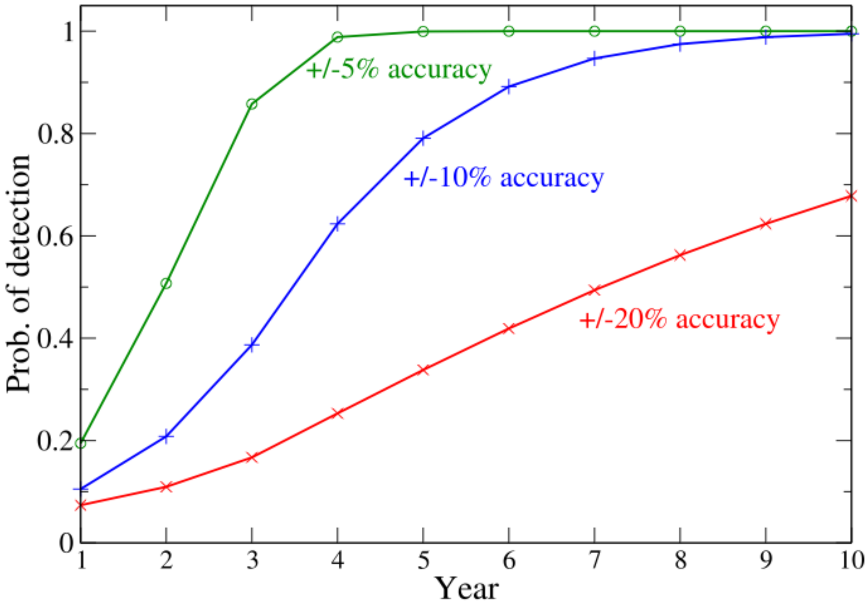

Figure 2-5. Cumulative detection probabilities for the "inflated baseline" scenario shown in Figure 2-1.

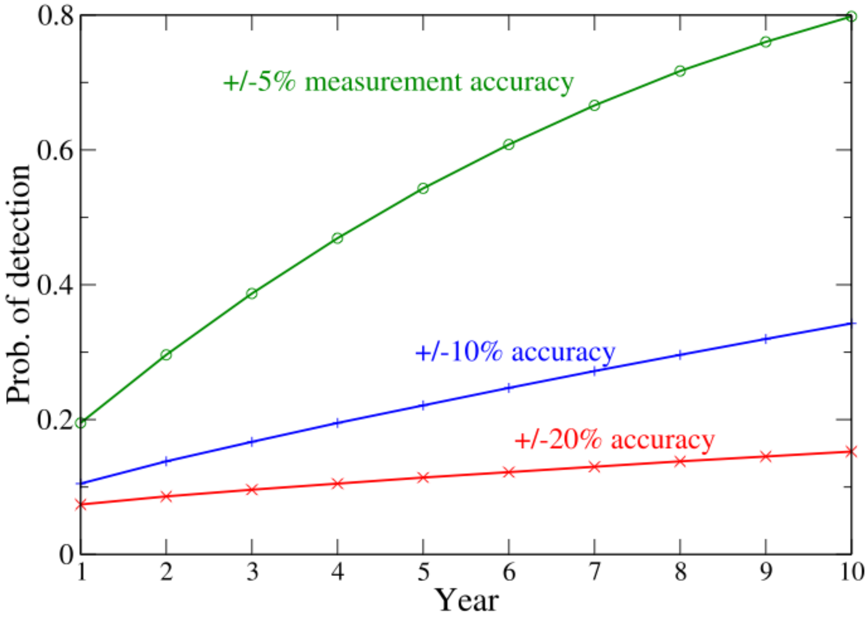

Figure 2-6. Cumulative detection probabilities for the "under-report" scenario shown in Figure 2-1.

The examples in Fig. 2-3 illustrate that required GHGIS uncertainty levels (accuracy) depend on how soon departures must be detected. High-level treaty targets may be made with a 10-year time horizon (e.g., the Kyoto Protocol). Validation of such high-level targets would certainly be an important function of GHGIS. However, substantial emissions growth and near-irreversible environmental damage can occur over a 10-year period, if countries are off target and unchecked. Most likely, one would wish to receive warnings, identify and notify emitters (domestic or international), and correct emissions departures on shorter time scales. If departures are the result of willful actions (cheating), one would wish to hold the administration accountable that committed the violation, or at least have a chance of doing so. A time horizon of 4 years in which to achieve the required detection probability may then be desirable. Table 2-1 summarizes the proposed accuracy requirements that flow from this consideration.

2.2.3 Emissions Scenarios

The discussion thus far focused on the detection of the BAU scenario. Figure 2-1 shows other emissions scenarios that depart from target emissions. These are discussed below.

> **BAU** (Business as Usual) Scenario – This follows a 1%/yr growth in emissions, roughly the average for the United States over the period 1990−2008. If the country of interest does nothing to reduce emissions, the gap between actual and target emissions will grow. This would present the easiest detection problem.
>
> **Partial Mitigation** – Emissions are reduced under this scenario, but at half of the needed rate (1%/yr instead of 2%/yr, relative to the baseline). This scenario is interesting because it would be difficult to detect based on infrastructure data and policies; the country is clearly undertaking mitigation measures and making reductions. The difference is in magnitude.
>
> **Inflated Baseline** – In this scenario, the country of interest misrepresents emissions in the baseline year (year zero), inflating them by, say, 8%. This allows the country to delay action for 4 years before beginning to reduce emissions at the target rate. Since GHGIS is framed as monitoring emissions relative to a *measured* baseline, it is not sensitive to what the target country declares as baseline emissions. An interesting feature of this scenario is that, for GHGIS, detection of the original baseline inflation becomes increasingly easy over time. In contrast, for many bottom-up methods, the best chance for detection occurs in the first year, when the absolute difference between stated and actual emissions is largest, and detection becomes increasingly difficult over time, and nearly impossible after Year 4.
>
> **Under-Reporting** – In this scenario, the country of interest under-reports emissions by, e.g., 2% each year, relative to the baseline, but after the first year, reduces emissions at the target rate. If the treaty framework allows for some kind of trading on emissions credits based on annual allowances, then the financial motivation for this scenario is clear. It poses a difficult detection problem for bottom-up methods as well as top-down GHGIS components, since it may fall within the uncertainty range of bottom-up inventory methods in any given year.

Figures 2-4 through 2-6 show the probability of detecting the departure for each of the additional scenarios. Implications in light of the proposed uncertainty/accuracy requirement are summarized in Table 2-1. Once again, it is a policy choice as to which scenarios are important to detect, but all of these may be of interest. If indeed all of the scenarios are of interest, and if GHGIS is framed as a system to measure absolute, total GHG emissions to be compared with country-level targets, then GHGIS must achieve uncertainties that are not much higher than ±5%. Although many assumptions were made to reach this conclusion, and reasonable alternative assumptions can certainly be made, it is unlikely that the general need to detect changes in emissions of, at most, a few percent per year can be avoided, which requires a GHGIS with uncertainties at the single-digit percent level. Accordingly, the present framing of GHGIS (as a tool to verify total, country-level emissions targets on an absolute scale) is centrally characterized by low-uncertainty (high-accuracy) requirements. As discussed in Chapter 7 and elsewhere, such uncertainty levels may be difficult to achieve. Other framings, discussed below, may allow this requirement to be relaxed to some extent.

2.2.4 A GHGIS Framed to Detect Departures from Relative Emissions Targets

Emissions targets are often stated as a fractional reduction relative to a baseline year. Emissions commitments of this type can be framed in terms of a relative reduction in emissions that does not necessarily depend on knowledge of baseline-year emissions with great accuracy. In this case, the GHGIS figure of merit is (integrated) measurement precision from one year compared with another, rather than accuracy on an absolute scale. Focus on precision mitigates sensitivity to year-to-year systematic errors. Another advantage is that such a GHGIS would not be sensitive to inflated baselines, i.e., over-reported emissions in a baseline year.

However, if GHGIS is to be relied upon to detect relative changes, it is advantageous from a monitoring perspective that it be operational in the baseline year. Existing treaties, such as the Kyoto Protocol and Montreal Protocol, have relied on historical baseline years. An advantage of this choice is that it is more difficult for participants to game the system (and further damage the environment) by ramping up emissions in the baseline year. However, baselines in the past pose measurement challenges and the choice of the baseline year is subject to some manipulation. For GHGIS to be used in this mode, a future agreement would need to use or somehow be linked to a baseline for which GHGIS could collect or had collected data, in which case the precision of the baseline-year measurements is particularly important.

In this context, GHG measurements from existing sensors and especially from space (because of their near-continuous extensive coverage) can play an important role, for example, from sensors such as Atmospheric Infra-Red Sounder (AIRS) (Chapter 3) that have been operating since 2002. While such measurement assets were not designed to support an operational GHGIS, year-to-year *changes* in detected GHG concentrations, even though not attributable by themselves to anthropogenic sources, can help reveal inconsistencies between declared emissions and measured concentrations in the reference baseline year. Similar benefits accrue an integrated system that can perform retrospective analyses of archived all-source data.

In the present framing, GHGIS measures total, annual emissions and compares them to single-value targets, much as in the previous framing. The analysis above of required accuracy still applies, except now one may replace “accuracy” with “precision” and can place the emissions trajectories in Fig. 2-1 on a relative scale (% change instead of $MtCO_2e$). Thus, an analogous conclusion as for the previous framing can be drawn: that this framing demands a high measurement *precision* to meet requirements. As stated above, the difference is that high precision will likely be easier to achieve than high accuracy because of common-mode rejection of certain systematic errors. However, this benefit may be diminished by year-to-year changes in infrastructure, population density, industrial activity, transportation-sector modalities, etc., and, not least, the environment itself. The remainder of this report primarily focuses on precision rather than accuracy.

2.2.5 GHGIS as a Check on Bottom-Up Inventories

In the previous two framings, measurements made by GHGIS each year are compared to another estimate, e.g., a target. Bottom-up inventories encompass a wealth of information, not just a single, annual emissions total. If the bottom-up inventory is considered as the "declaration," i.e., what the country reports to be true and its best estimate, then inventory verification and validation becomes equivalent to target verification and validation. In this framing, the declaration, once verified, validated, and certified, becomes the official emissions record for that year, against which consistency with treaty obligations may be judged. Declared emissions need not match target emissions, but if the country declares emissions higher than target, they may be expected to undertake appropriate actions, such as buy emissions credits to make up the difference, undertake other verifiable offset/mitigation actions, or pay some penalty.

A consequence of this framing is that GHGIS must allow for uncertainties and errors inherent in the inventory process. That is, one would expect an inventory made in good faith to sometimes miscount, or undercount emissions. This effectively broadens or shifts the "noise" distribution against which GHGIS attempts to detect errors (intentional or not) in the inventory. Suppose that Midlandia submits an inventory with ±5% uncertainty, as is reasonable for a well-developed inventory. Per above, the uncertainty would best be narrower if the interest is year-on-year changes rather than absolute accuracy.

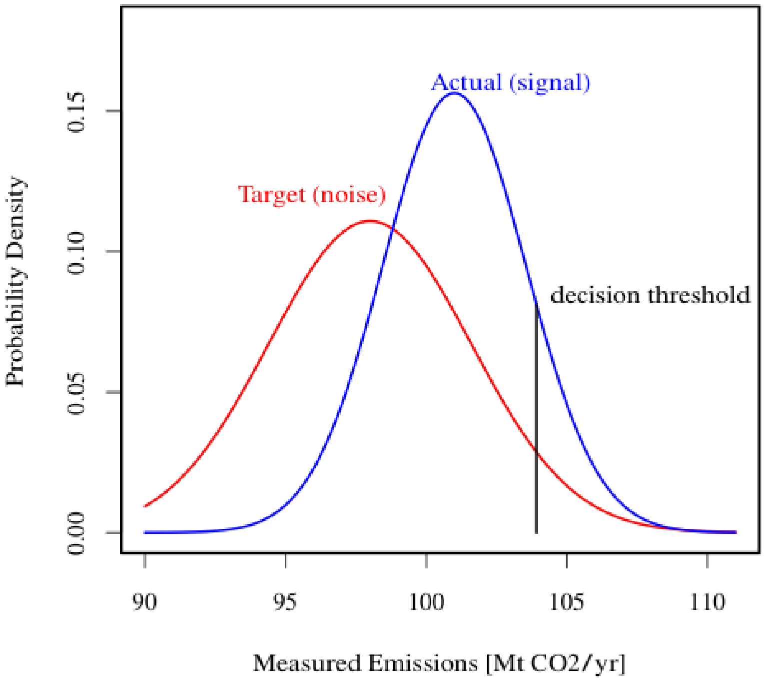

Figure 2-7. Distribution of measured values given compliance (at emissions = 98) and noncompliance (at emissions = 101, "actual"), with an estimation uncertainty of ±5% and a decision threshold of 95% confidence (5% false-positive rate, analogous to Fig. 2-2), adding ±5% uncertainty in the bottom-up inventory (the declared emissions value) for an inventory to be verified. Departure detection is less likely (compared with Fig. 2-2) because some high measured values result from random under-reporting within the inventory uncertainty range.

Figure 2-7 shows a detection problem analogous to that depicted in Fig. 2-2 with this inventory uncertainty factored into the noise distribution. The wider noise distribution compels setting a higher decision threshold, reducing the probability of detection to 13%, compared with 32% if the inventory value was accepted as error-free. When GHGIS is used as a check on declared emissions, improving the accuracy of bottom-up inventories increases the value of GHGIS by making detection easier. This conclusion may run counter to intuition that GHGIS is less valuable when good inventories are available, which stems from framing top-down and bottom-up methods as equally important components, as discussed above.

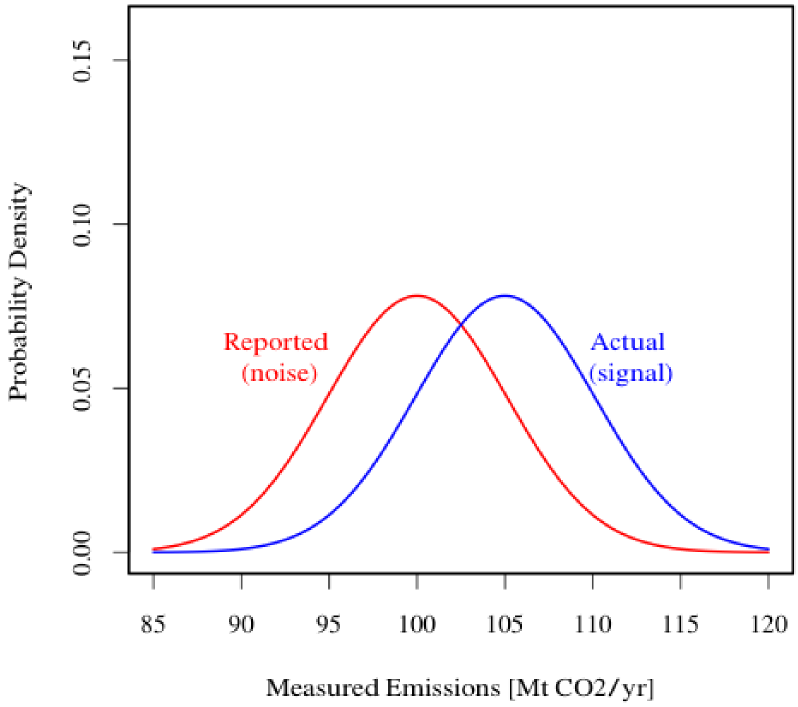

Figure 2-8. Distribution of measured values given compliance (at emissions = 100, "Reported") and noncompliance (at emissions = 105, "Actual") with a measurement uncertainty of ±10%.

Although detection may be more difficult in the presence of inventory uncertainty in this framing, the wealth of inventory information can render detection easier. At least, one has information about economic-sector (sectoral) emissions. GHGIS could also estimate sectoral emissions and then compare values with inventory reports, yielding improved chances to identify inconsistencies. One can also make multiple measurements in the same year.

Suppose, for example, that GHGIS can attribute Midlandia's emissions into four sectors: coal, petroleum, natural gas, and non-CO_2. For simplicity, assume that measurements of these sectors are independent and that the total is calculated by summing them (in reality, measurement of ratios among the sectors and the total to make the attribution is more likely, but the conclusions are similar in either case). Suppose also that Midlandia's reported emissions from each of the four sectors are equal, e.g., 25 Mt/yr each for a total of 100 Mt/yr, and consider the detection scenario of determining whether Midlandia's total emissions are 5 Mt (5%) above target.

If each sector is measured with a relative uncertainty of ±20% and if, for the purposes of illustration, uncertainties are dominated by random uncorrelated (independent) errors with an equal probability of being positive and negative, then estimated total emissions would have a relative error of ±10%, since, for n equal sectors ($n = 4$ in this example) with such uncertainties, the relative error of the sum would decrease by $1/\sqrt{n} = 1/2$. However, if inventory errors are all of one sign and correlated, e.g., from inadvertent or intentional underreporting, then the fractional uncertainty of the sum remains that of the (relative) uncertainty of each component and, in particular, does not decrease with n. The important issue and consequences of the apportionment of uncertainties (errors) into random (aleatoric) and systematic (epistemic) is discussed later in this report in the context of spaceborne sensor data (Chapter 3), data uncertainty quantification (Chapter 6), and modeling and modeling uncertainty quantification (Chapter 7).

Figure 2-8 illustrates the detection problem when considering only total emissions. However, sectoral attribution allows the incorporation of external pieces of sector-specific information. Suppose, for example, that independent information is available that leads one to believe that Midlandia’s emissions are off-target by 5 Mt/yr because of growth in their coal-sector emissions. Figure 2-9 illustrates the detection problem sector by sector. In three sectors, target emissions match reported emissions, so measurements trigger no detection. In the coal sector, however, departure from reported emissions is larger relative to GHGIS precision than for the total. There is then a 62% chance of detecting this scenario at the 95% confidence level, as opposed to 25% if one considers total emissions alone.

Absent information identifying the sector in which the departure is occurring, localizing emissions departures to one sector would not be as helpful as it appears. One would expect such a measurement to occur by chance four times as frequently, so one would have to set a higher decision threshold for similar confidence.

Although currently not required by the UNFCCC process, bottom-up inventories could be expanded to break out emissions by region. Many states and provinces already produce GHG inventories. Inventories could also resolve emissions on a shorter time scale, perhaps quarterly or monthly. These expansions would allow GHGIS to make comparisons with regional and temporal emissions values, providing additional comparisons to certify inventory consistency.

An advantage of such a framing of GHGIS would be its incorporation of external information to constrain the detection problem (as in the example above), to confirm inferences from other means of detection, or to focus further investigation to a particular sector, region, or time period. Verification methods of bottom-up inventories, e.g., audits of economic data, could be triggered by measurements of high emissions in a particular area. Thus, this framing provides substantially more flexibility and potential for integration with other methods, somewhat reducing thereby the burden on GHGIS of high precision. However, a trade is made between integration of other information to constrain and improve assessments and detection, and treating other information as independent, to be used as a consistency check of GHGIS assessments.

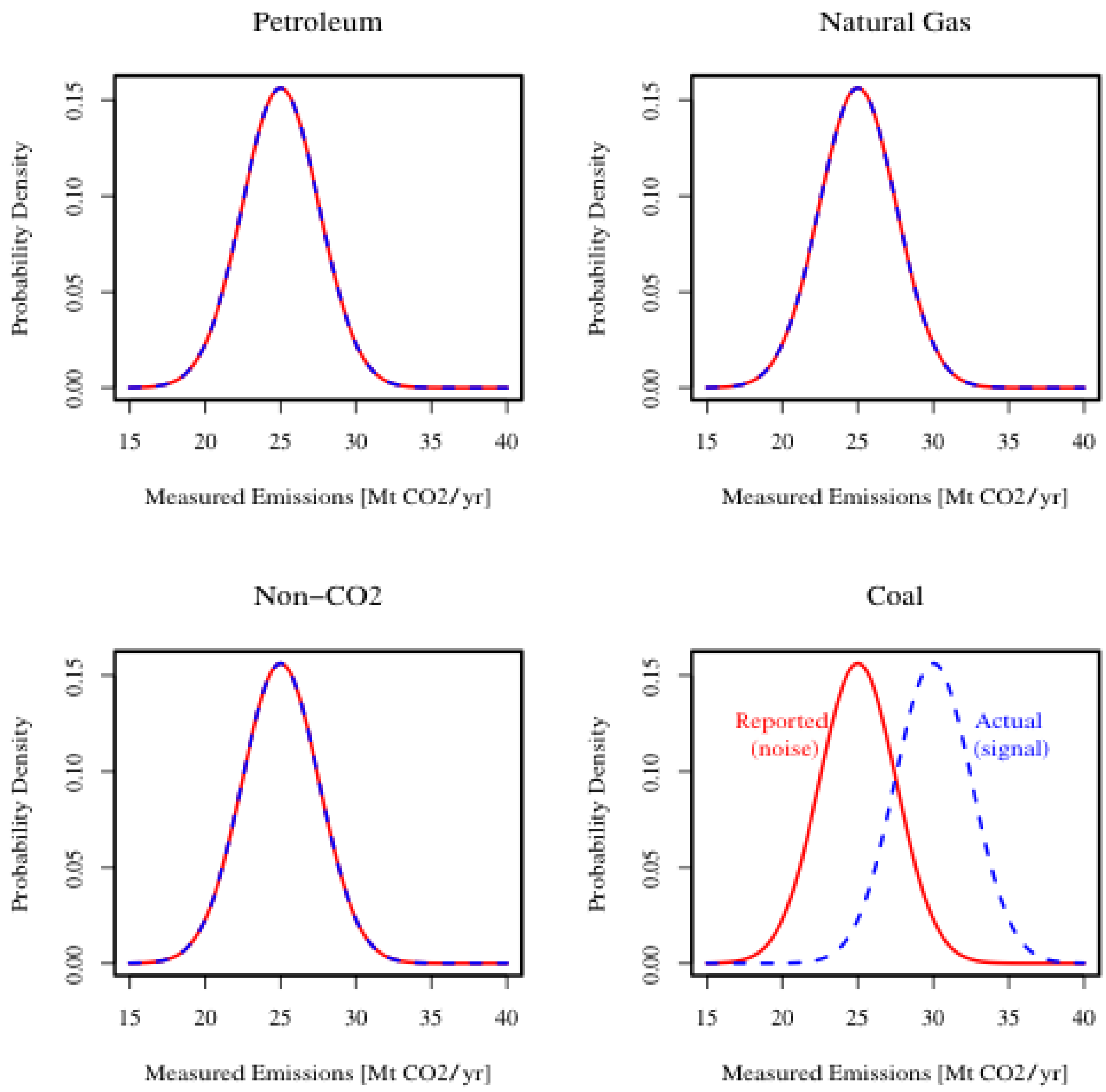

Figure 2-9. Representation of the detection problem in Fig. 2-8, broken into four sectors, given external information that the departure occurs in the coal sector. Each sector is measured with a relative uncertainty of ±20%. The departure is more easily detected than for the scenario in Fig. 2-8 (no sectoral attribution).

2.2.6 Framing GHGIS to Verify Mitigation Actions

Previous framings focused on GHGIS providing quantitative measures of GHG emissions, the primary focus of this report. However, elements of GHGIS can be used to validate mitigation activities, or commitments, such as construction and operation of renewable-energy sources, reforestation and afforestation, or shuttering of coal-fired power plants. For example, Brazil committed to reduce deforestation by 80% by 2020, as measured by land area (Tollefson 2010). Similarly, elements of GHGIS may be used to verify mitigation actions that, in turn, signal compliance with an emissions commitment, such as the absence of new coal-fired power plants.

Satellite imagery in particular can be used to assess reports of large-scale mitigation measures. Large power plants will show up as hot spots in a CO_2 concentration map, signaling their operation and when they are taken off line. Trends in certain non-CO_2 tracers may also signal the presence or absence of mitigation measures, such as electric-vehicle use, or ethanol fuel blends in vehicles.[4] Such signals may be important during Phase 1, when quantitative measurements will not be sufficiently precise. Validation of mitigation actions was discussed in Chapters 1 and will be covered further in Chapter 3.

2.2.7 Conclusion and Working Assumptions

A challenge of validating single-point emissions targets is the high precision required (±5%) to meet detection goals. For this reason, a GHGIS may best be used in conjunction with bottom-up inventories that provide multiple comparisons and aid integration of external information into the detection process. As a consequence, GHGIS should (also) be capable of providing sectoral attribution and, potentially, regional and sub-annual emissions estimates in addition to country-level totals. Such capabilities can enhance detection probabilities with lower precision levels.

To characterize the usefulness of an integrated system, the probability of detection provides a better metric than high-level uncertainty (accuracy or precision). However, such a metric depends on factors that cannot be quantified in this report, such as how well anthropogenic emissions can be discriminated in a background of (large-amplitude) natural/biogenic emissions and how well economic/energy/industrial sectors can be distinguished, what external information is available, and how reliable that information is. As an initial benchmark, a goal of ±10% precision for annual emissions from high-emitting countries can be considered. This goal recognizes the value of a reliable total emissions estimate and of not relying too heavily on external information. Note also that the term “precision” is used because the proposal is to focus on relative changes in emissions rather than absolute totals.

2.3 Spatial Resolution

GHGIS data analysis and reporting will be characterized by a number of spatial scales. These need not be the same for measurements and reporting. They include the data-retrieval horizontal resolution dictated by the density of a ground-sensor network, the horizontal and vertical resolution of measurements from airborne and space sensors, the horizontal resolution and quality of local and regional emissions-inversion models (“the retrievals”), and the scale on which local, sub-national, and national emissions are estimated for reporting. A GHGIS goal of emissions estimates is retrieval at the country level. However, when sub-national information is available for comparison, retrievals at sub-national scales add value. This may include state- or province-level emissions in larger countries, or emissions from particular metropolitan areas, or regions of intense industrial activity.

Metropolitan areas offer an opportunity because they produce high local CO_2 concentrations compared with background emissions, yielding strong signals in atmospheric samples. They also represent distinct and contained emissions sources compared with an entire country. These two

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[4] Ethanol fuel blends result in a different emissions profile at the vehicle.

features together may allow for greater precision in emissions measurements. While metropolitan area emissions are not surrogates of country-level emissions, they can provide useful year-by-year comparisons and a bellwether of national emissions trends.

As a consequence, required horizontal spatial scales will likely vary from country to country. As a benchmark, an initial horizontal spatial resolution for anthropogenic emissions estimates in the range of 10 to 50 km may be adopted for reporting purposes, with refinements, as necessary, to capture sub-country (regional) emissions. A 10- to 50-km horizontal resolution would allow sub-national emissions estimates for larger countries, although at this scale, some smaller countries may not be readily distinguishable from their neighbors. Higher-resolution measurements and retrievals could address stricter monitoring and reporting requirements.

For comparison with bottom-up inventories, GHGIS measurements of most interest are in the lower part of the atmosphere, particularly the part of the troposphere known as the planetary boundary layer (PBL). The PBL is typically contained below an altitude of 0.5 to 1.5 km.[5] Measurements made at higher altitudes in the atmosphere, e.g., at mid-troposphere or stratosphere altitudes, can provide year-to-year tracking of emissions trends, constraining transport models, and improving understanding and characterization of the carbon cycle, but are not as useful as lower-troposphere, near-surface, or ground-level measurements are for constraining surface fluxes or emissions attribution directly.

2.4 Temporal Resolution

Similar to spatial resolution, GHGIS measurements and reports will be characterized by a number of temporal scales: the temporal resolution of measurements by the various sensors, of the inversion model, and the resulting emissions estimates. It would be desirable if the frequency of official reported emissions estimates matched the temporal scales of other reported data against which they will be compared – chiefly, the schedule of emissions targets and release of bottom-up inventories. Both of these are, at present, typically annual. Other information of interest may include economic reports, many of which are released quarterly, and energy statistics (such as fuel sales) that are sometimes available monthly. GHGIS should provide official emissions estimates on an annual basis, along with quarterly interim reports that could be subject to subsequent updates and revision. Quarterly reports would provide a comparison with sub-annual economic data and energy statistics and serve as early indicators of emissions trends in any given year, helping stabilize future carbon markets.

Another time scale of interest is the lag time between the completion of a measurement year and the release of the official emissions estimate. A variety of factors will contribute to lag time: some in situ samples must be physically shipped and analyzed, data must be vetted for quality assurance and quality control (QA/QC), data UQ analysis must be performed and passed through various organizations, and instrumentation may need to be checked and recalibrated. Bottom-up

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[5] Transport within and through the PBL presents great emissions retrieval challenges. Mixing within it is rapid during daylight hours so retrieval of upwind emissions information is made difficult because of the enhanced dispersion. Further, night-time transport occurs in a stratified atmosphere governed by totally different, if perhaps more tractable, dynamics. Finally, PBL height and behavior within it depends on orography and upwind-terrain details, all of which contribute complexity and uncertainty in the face of modeling and wind-field uncertainties.

inventories against which the top-down estimates are to be compared also have a significant lag time. Inventories are currently submitted to the UNFCCC, by legal requirement, with a lag time of about 16 months. While a future international agreement may stipulate shorter lag times for inventories, a significant delay is still expected. Inventories depend on surveys and reporting by businesses and various organizations. The data must be checked, compiled, and reviewed. It may prove difficult for this process to be completed in much less than a year. All considered, the proposed GHGIS should not add to this delay and should accept a goal of no more than a one-year lag time.

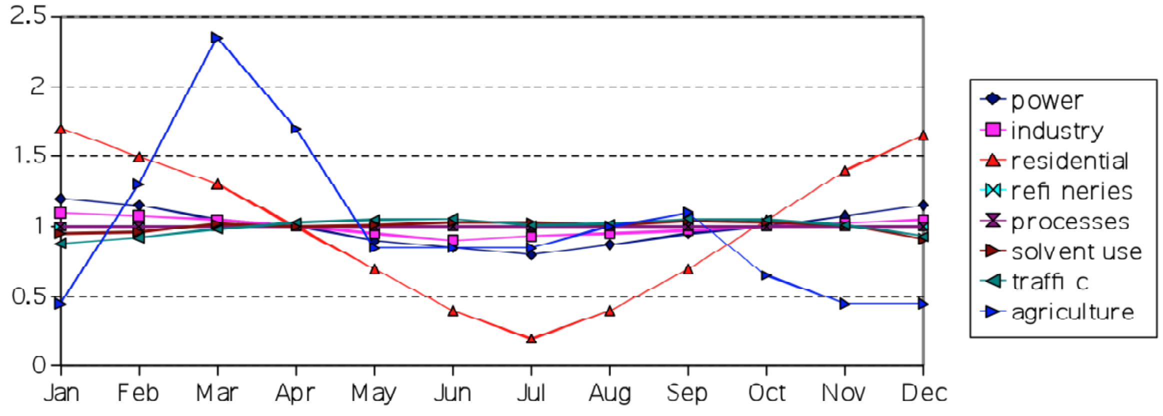

Figure 2-10. Average relative monthly variation in GHG emissions by sector (EDGAR 2009).

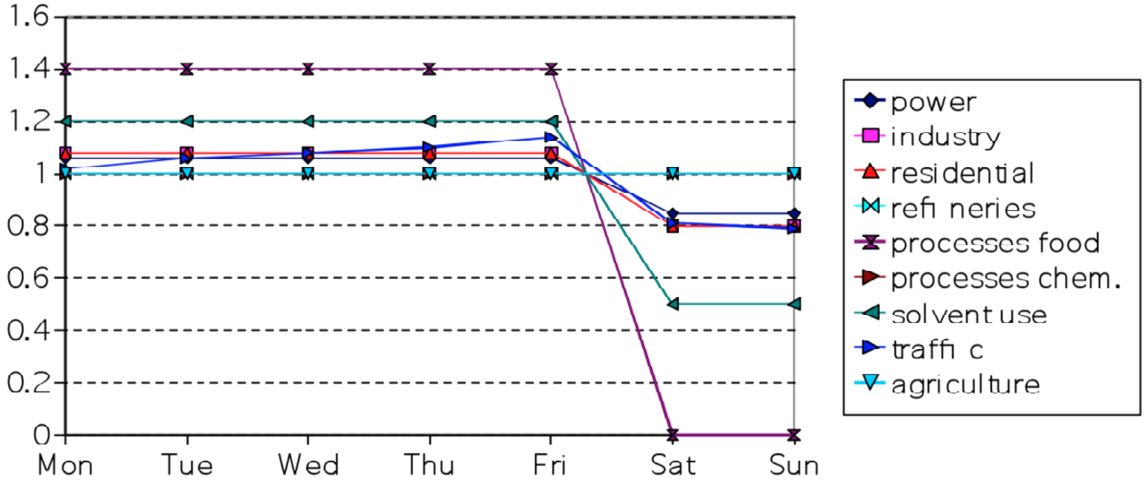

Figure 2-11. Average relative day-of-the-week variation in GHG emissions by sector (EDGAR 2009).

While emissions estimates are reported annually and quarterly, GHGIS must internally aggregate emissions-related measurements on a variety of shorter time scales. GHG emissions vary substantially on seasonal, weekly, and daily cycles. Figures 2-10 through 2-12 illustrate the variation of these cycles in the Emissions Database for Global Atmospheric Research (EDGAR). GHGIS instrument systems will need to resolve these cycles (e.g., with hourly measurements), average over them in a manner that minimizes bias, or normalize/compensate for them using time profiles of emissions like those shown. Profiles would need to be developed for each area measured and, if based on self-reports by target countries, would need to be verified and validated to address the possibility of manipulation. Handling the temporal cycles is an important issue. Proposed approaches will be discussed in the sensor chapters

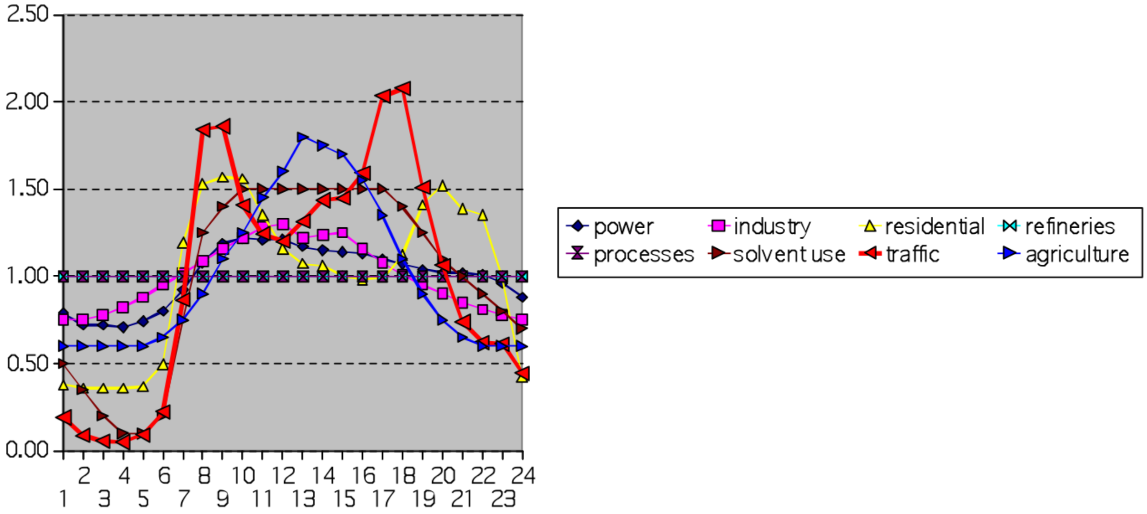

Figure 2-12. Average relative diurnal (hourly) variation in GHG emissions by sector (EDGAR 2009).

2.5 Country Coverage

The choice of which countries should be monitored by GHGIS is influenced by which countries make commitments, which countries allow access, and which contribute significantly to global emissions. In order to stabilize atmospheric concentrations of CO_2, global emissions cuts of *at least* 80% will be required (NRC 2010b). Thus, if GHGIS is to support stabilization, GHGIS would eventually need to cover countries that contribute the vast majority of global emissions. A Phase 2 goal of covering at least 80% of emissions, by country, is proposed.

The picture of how many and which countries must be covered is slightly different depending on which gases are included, whether emissions related to land-use change are included, and whether the EU is considered as a single entity with a collective emissions target (following the model of the Kyoto Protocol), or whether its 27 member countries are considered individually. Figures 2-13 and 2-14 show, in a sense, the two extreme perspectives. Figure 2-13 shows only fossil CO_2 emissions with the EU considered as one entity and Figure 2-14 shows total GHG emissions including land-use change with the EU disaggregated. In the former case, the top eight emitters cover 80% of the global total, and in the later case, 28 countries must be measured.

In light of the varying perspectives, a list of countries that must be covered, which will also be driven by other considerations, is not proposed here. However, the figures illustrate the size and type of countries that GHGIS should be capable of monitoring. Further, these rankings will change, evolving with time, albeit slowly.

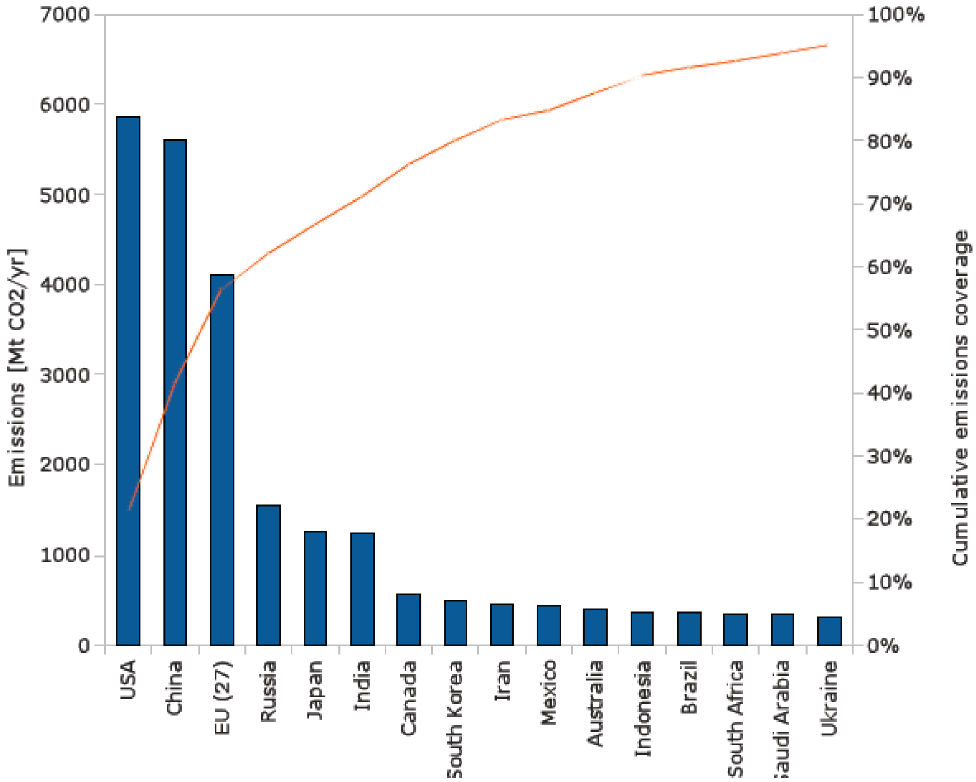

Figure 2-13. Top fossil CO_2 emitters and cumulative emissions coverage (red line), with the European Union considered as one emitter. Based on emissions data for 2005 (WRI 2010).

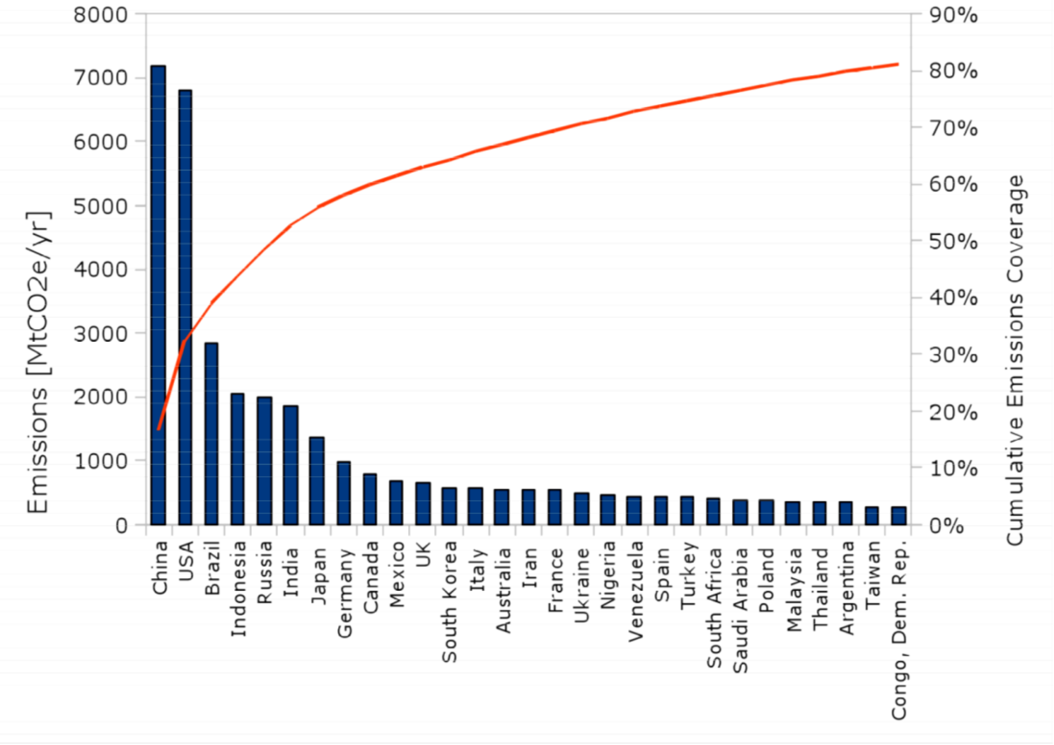

Figure 2-14. Top GHG emitting countries and cumulative emissions coverage (red line) with the EU disaggregated into member countries. Based on emissions data for 2005 (WRI 2010).

2.6 Coverage by Gas

Figure 1-1 in the Introduction (Chapter 1) shows the share of total global GHG emissions by gas, in CO_2 equivalents, based on the global warming potential of each gas. CO_2 is further broken into fossil-derived emissions and natural/biogenic emissions. CO_2 from fossil sources comprises only about 60% of emissions. Countries may make commitments to total GHG emissions, as they have in the Kyoto Protocol. Coverage of non-CO_2 GHGs and non-fossil CO_2 will be required if the GHGIS is to achieve meaningful validation of targets.

The share of non-fossil CO_2 and non-CO_2 gases varies by country, with fossil CO_2 being relatively more important in industrialized countries. For example, in the United States, fossil CO_2 represented 84% of gross GHG 2005 emissions. However, CH_4 and N_2O are significant, comprising 8% and 6% of emissions. In China, CH_4 and N_2O represent 12% and 10% of emissions in the same year, a somewhat larger share. Fluorinated gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) together) generally represent than 2% of national emissions. Of the top emitters, the United States has the largest share attributed to fluorinated gases, comprising about 3% of total emissions (WRI 2010).

Assuming an interest in relative *changes* in emissions, a gas contributing a significant share, but which does not change much over time, could perhaps be omitted from the monitored list. CH_4 and HFCs would not be good candidates, however, because they represent opportunities for near-term, low-cost mitigation efforts (EPA 2006). An argument might be made to omit N_2O on this basis; N_2O emissions have been essentially flat in the United States since 1990, for example (EPA 2010). Mitigation opportunities and their efficacy for N_2O (primarily associated with agriculture) are hard to quantify and less well-developed than for other gases. Whether N_2O must be included to achieve the overall required precision depends on expectations on the future role of N_2O mitigation. To maintain maximum GHGIS functionality, N_2O should be included.

In summary, a GHGIS is proposed that covers all GHGs necessary to allow confident measurement of total anthropogenic emissions trends, with ±10% precision. In particular, GHGIS must monitor fossil CO_2, biogenic CO_2, CH_4, N_2O, and the majority of fluorinated gases.

2.7 Attribution by Sector

As discussed above in the section on framing, attribution of emissions to sector (that is, attribution either by the type of emitting source or the type of fuel used) offers a number of potential benefits. Sectoral attribution allows detailed comparison with bottom-up inventories, the incorporation of sector-specific external information, and detection of departures even with lower monitoring precision. For effective comparison with bottom-up inventories, GHGIS should be capable of attributing emissions to, at least, the following sectors, or categories:

- biogenic (non-fossil) CO_2,
- coal-power CO_2,
- petroleum-based transportation CO_2,
- natural-gas CO_2 from heating and cooking,

- discrete events, such as forest fires or oil-spill burning, and
- select large-scale natural events, such as volcanic eruptions.

As discussed in later chapters, sector attribution is possible by measuring isotopes, such as ^{14}C and ^{13}C, and co-emittants, such as carbon monoxide (CO). Different source types and fuels have different isotopic and co-emittant signatures. High spatial resolution of the sensor network and of emissions estimates can also aid attribution when combined with information about the geographic distribution of certain source categories (e.g., emissions in an urban grid square are more likely associated with transportation while emissions in a rural grid square are more likely biogenic). Specific techniques and capabilities for attribution will be discussed in later chapters.

2.8 Conclusions

A high-level requirements framework for GHGIS as a tool to monitor and verify international emissions targets and treaty commitments has been discussed. Since the nature of future emissions-mitigation commitments is unknown, an attempt was made to keep the discussion general, with necessary assumptions made to reach the quantitative conclusions above. In the analysis of alternative framings of GHGIS, the conclusion was reached that the most practical framing is to consider GHGIS as a tool to measure relative *changes* in emissions and compare those with reported changes in bottom-up inventories.

The required precision with a number of quantitative examples was explored, which, although simplified, illustrates a robust conclusion, i.e., that the precision eventually required for monitoring anthropogenic emissions for an operational GHGIS is close to ±10%. This assumes a GHGIS capable of multiple comparisons with bottom-up inventories or other information.

The ability to compare GHGIS results with inventories and external information drives several other requirements: GHGIS should be capable of attributing emissions to at least a handful of separate sectors, resolving emissions regionally in larger countries, and resolving emissions on a variety of time scales.

The choice of which gases to cover is driven by the assumption that future commitments will be made on total GHG emissions and not on CO_2 alone. To achieve high-precision measurements of the total, CO_2 (both fossil and non-fossil), CH_4, N_2O, and the majority of fluorinated gases (HFCs, PFCs, and SF_6) must be monitored. However, the primary focus of this report is fossil CO_2.

On the question of which countries to cover, covering 80% of global emissions is proposed. The choice of the particular countries to cover represents a separate (political/policy) issue. However, the list may reasonably include tens of countries, including countries on every continent except Antarctica and with every type of terrain, with countries ranging in area from 36×10^3 km^2 (Taiwan) to 17×10^6 km^2 (Russia), and ranging in latitude from 83˚N (northernmost tip of Canada) to 56˚S (southernmost tip of Argentina).